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A WAVELET-BASED APPROACH FOR ONLINE EXTERNAL LEAKAGE DIAGNOSIS AND ISOLATION FROM INTERNAL LEAKAGE IN HYDRAULIC ACTUATORS

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Abstract

This paper presents experimental evaluation of applying wavelet transform for on-line external leakage fault detection and isolation from internal leakage in hydraulic actuators. In this work, the more realistic case of an actuator that is driven to track pseudorandom position reference inputs against a load is considered. The wavelet-based method developed in this paper, decomposes a limited-duration pressure signal at either chamber of a hydraulic actuator into effective approximate and detail wavelet coefficients. The limited-duration pressure signal is collected using a sliding window technique. It is shown that the root mean square (RMS) value of the level four approximate wavelet coefficient collectively establishes a feature index that can effectively be used for on-line detection of external leakage. Once the external leakage occurs, this index value decreases proportionally. Therefore, one can report the faulty operating condition by monitoring this index. Additionally, built upon the previous work in which the level two detail coefficient was found to be sensitive to internal leakage fault, we further investigate the isolation of external leakage from internal leakage in an actuator. Extensive validation tests demonstrate the effectiveness of the proposed technique, given any position reference input, loading condition, and controller type or effectiveness. Experimental tests show promising results for detecting external leakage as low as 0.3 L/min and isolating it from internal leakage as low as 0.48 L/min, during an on-line testing procedure.

Keywords: hydraulic actuators, external/internal leakage, on-line fault detection, wavelet analysis

1 Introduction

Due to their overall reliability and high power-to-weight ratios, hydraulic actuators see widespread use in a variety of industrial applications. Reliability and safety are important issues in most of the above applications. Thus, condition monitoring of fluid power systems is earning consideration to reduce the cost of maintenance and prevent the system from further deteriorating. Towards this goal, it is desirable to develop fault diagnosis (FD) schemes that can report abnormal conditions in hydraulic systems (Isermann, 1996). Online diagnosis of faults in hydraulic actuators is important to avoid further deteriorating of the system reliability and performance. FD systems can also be effectively used with active fault tolerant controllers that are designed to react to the changes in the system's parameters due to faults, through adaptation or reconfiguration (Karpenko and Sepehri, 2003).

Faults in hydraulic systems cover a wide range, from component failure and fluid contamination, to pipe leakage and material wear (Khan et al., 2002; Zavarehi et al., 1999). However, one of the greatest concerns regarding hydraulic actuators is the leakage of hydraulic fluid. Depending upon whether the hydraulic fluid is lost to the atmosphere or is displaced to another location within the hydraulic circuit, leakage can be classified as external or internal respectively. Wear of the seals separating the actuator rod and the cylinder results in external leakage. External leakage can also be caused by failure of hydraulic supply line or connection between the valve and the actuator's chambers. Internal leakage fault is caused by the wear of piston seal that closes the gap between the moveable piston and the cylinder wall. Both external and internal leakages, affect the dynamic performance of the system since the entire flow is not available to move the piston against a load.

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Condition monitoring of hydraulic systems can be done using off-line or on-line approaches. In off-line approach, a structured predefined input signal is normally applied to the system under ideal (no-load) condition. Information on the system response, obtained over the entire test period, is then used for diagnosis. In on-line approach, data on the states of the system are obtained and analyzed while the system is operating through its routine work cycle. Within the context of hydraulic actuation, this implies the actuator must track reference position signals of various magnitude and duration and under various loading conditions. An example would be positioning of an aircraft control surface. As opposed to off-line approach where the diagnosis can be conducted using responses from the system under open-loop control, the on-line approach uses data from the system operating in a closed-loop position control mode. Thus, the diagnosis method should preferably function independent from the controller type or effectiveness. Furthermore, during the on-line approach, information is obtained from limited-duration segments of the continuous stream of measurements collected on-line. On-line fault detection is more interesting than the off-line one, since it provides information about the health of the system without interrupting its routine operation. It can also provide a support for active fault tolerant controllers to reconfigure their control actions in response to changing conditions due to occurrence of faults.

A great deal of work has been carried out on development of fault detection and isolation (FDI) systems (Watton, 2007). A detailed survey on existing techniques has been provided in reference (Watton, 2007). However, research on actuator leakage fault identification, in spite of its importance, is still limited. Tan and Sepehri (2002) applied the Volterra nonlinear modeling concept for offline detection of actuator leakage faults. The method reported in (Tan and Sepehri, 2002) required a model of leakage. Leakage is a kind of non-ideality that cannot be modeled exactly (Garimella and Yao, 2005). Thus, the uncertainty associated with modeling leakage can become an issue within the framework of model-based fault detection. An and Sepehri (2005) studied the feasibility of using extended Kalman filter to detect actuator internal and external leakage faults with sinusoidal reference input. They further extended this work towards online detection of internal and external leakages by including both friction and loading as unknown external disturbances (An and Sepehri, 2008). In their work, a high gain proportional controller was used to track the reference input. Although the requirement of using a model for leakage was removed in An and Sepehri (2005, 2008), the need for knowing the model of hydraulic actuator still remained a challenge. In order to overcome the difficulties associated with modeling nonlinear hydraulic systems, a linearized model with an adaptive threshold, to compensate for the error due to linearization, was used by Shi et al. (2005) to detect internal and external leakage faults. Le et al. (1998) proposed a neural network approach to detect both internal and external leakages in a hydraulic actuator even when they happen at the same time. To obtain the feature signals, they excited the system in a closed-loop scheme with a step input under no-load condition. Their results showed detecting leakages over 1 L/min, which is considered to be high. Small leakages are most interesting for early detection of faults.

Motivated by developing a method that does not rely on a model of the system or fault, the authors initiated a research directed at employing the wavelet transform to detect leakage in valve-controlled hydraulic actuators. Wavelet transform is essentially an extended time-frequency yielding wavelet coefficients at different scales (levels) (Daubechies, 1992). The technique has recently drawn widespread attention as a promising tool to deal with fault detection by extracting feature patterns from spectral signals. To name a few, Zhang and Yan (2001) developed a wavelet-based method for detection of different kinds of sensor faults. Gao et al. (2003) employed wavelet transform for on-line hydraulic pump health diagnosis. The pulsation pressure signal was used and faults due to malfunctioned pump were isolated based on the detail wavelet coefficients. Wavelet transform method was also shown to be more sensitive and robust than the spectrum analysis approach, in detecting faults associated with hydraulic pumps (Gao, 2005). Goharrizi and Sepehri (2009, 2010a, 2010b) used wavelet transform for both offline and online internal leakage detection. They showed that internal leakage alters the transient response of pressure signal at any chamber of the hydraulic actuator. This characteristic appears clearly in finer scales, represented specially by level two detail coefficient. The transform technique was recently examined to detect external leakage (Goharrizi and Sepehri, 2011). Level four approximate coefficient of pressure signal was effectively used in an off-line manner.

Built upon the work reported earlier (Goharrizi and Sepehri, 2010b; 2011), this paper establishes a framework for online detection of external leakage and isolation of it from internal leakage when they occur singly in a multiple-fault environment. A more realistic case of an actuator that is controlled to follow arbitrary reference position signals against a load is considered. As opposed to internal leakage, external leakage alters the steady state pressure signal with negligible effect on the transient pressure signals. To make the approach applicable to on-line applications, a sliding window technique is applied, whereby segments of measured pressure signal from one side of the actuator are collected, and the root mean square (RMS) value of the level four approximate wavelet coefficient vector obtained from each window, is calculated as an index during the run time. It is shown that once external leakage happens, this index decreases proportionally with the leakage level. Furthermore, isolating external leakage from internal leakage in a multiple-faults environment is shown to be possible throughout the results presented in this paper. It is shown that the level four approximate and level two detail coefficients are independently sensitive to external and internal leakages, respectively. Therefore, by simultaneously monitoring level four approximate and level two detail coefficients, one can detect and isolate external leakage from internal leakage in an actuator where its displacement is controlled in a closed-loop scheme. In the present work, these faults are assumed to occur singly but exist in a multiple-fault environment.

The effectiveness of the proposed approach is validated through extensive experiments, designed for a hydraulic actuator that tracks pseudorandom position reference signals against a load which is emulated by a spring. Detecting small leakages is the focus of this paper since they are most interesting for early detection of fault. The proposed approach is shown to, not only detect external leakages as low as 0.3 L/min, regardless of the reference input and loading conditions, but also is capable of isolating external leakage from internal leakage in a multiple faults environment. The method is easy to implement as it only needs one measurement. It is also capable of detecting the leakage, even with a controller that still maintains good positioning when leakage occurs.

The rest of this paper is organized as follows. Section 2, describes the experimental hydraulic system as application domain. Section 3 provides a brief description of signal decomposition using wavelet transform. Section 4 shows experimental results describing how the proposed wavelet-based approach is used to identify and isolate the external leakage fault from the internal leakage. Conclusions are given in Section 5.

2 Experimental System

The hydraulic actuator test rig upon which all tests are conducted is shown in Fig. 1. Powered by a motor-driven hydraulic pump, the actuation system operates with the fluid pressure of 17.2 MPa (2500 psi). The movement of the actuator (with a 610 mm stroke) is controlled by a high performance Moog D765 servovalve with the flow capacity of 34 L/min at 21 MPa supply pressure. The valve accepts analog command signals from a high-speed PC equipped with a data acquisition board. The displacement of the actuator is obtained by a rotary optical encoder via a Metrabyte M5312 quadrature incremental encoder card and the chamber pressures are measured by sensors located at each side of the cylinder. Figure 2 shows the schematic of the test rig. The manner in which leakage fault is produced is also shown in this figure. With reference to Fig. 2, to create external leakage, a portion of the fluid flow from either side of the actuator, is bypassed to the reservoir by opening the corresponding needle valves (see the inset in Fig.1). External leakage flows, q_{el1} and q_{el2}, are measured using positive-displacement flowmeters (JVA-KL series by AW Company with a 7.6 L/min range and accuracy of ± 0.5 %). The internal leakage is produced by bypassing fluid across the piston. This is achieved by connecting the two chambers of the actuator and controlling the flow by an adjustable needle valve (see also Fig. 1). The internal leakage flow rate q_{il} is also measured by a positive displacement flowmeter.

The positioning of the actuator against the spring load is achieved according to the two-degree-of-freedom feedback system configuration shown in Fig. 3. The controller, $G(s)$, and the prefilter, $F(s)$, are designed to satisfy the desired closed-loop performance specifications. The controller used here has been designed using the quantitative feedback theory (QFT) and is tolerant to model uncertainty and certain leakage fault types associated to hydraulic actuators (Karpenko and Sepehri, 2010). The structure of this controller is shown below:

$$C(s) = \frac{3.18 \times 107(s+12)}{s(s^2 + 225s + 250^2)} \tag{1}$$

$$F(s) = \frac{25(s+13.5)}{(s+8.5)(s+35)} \tag{2}$$

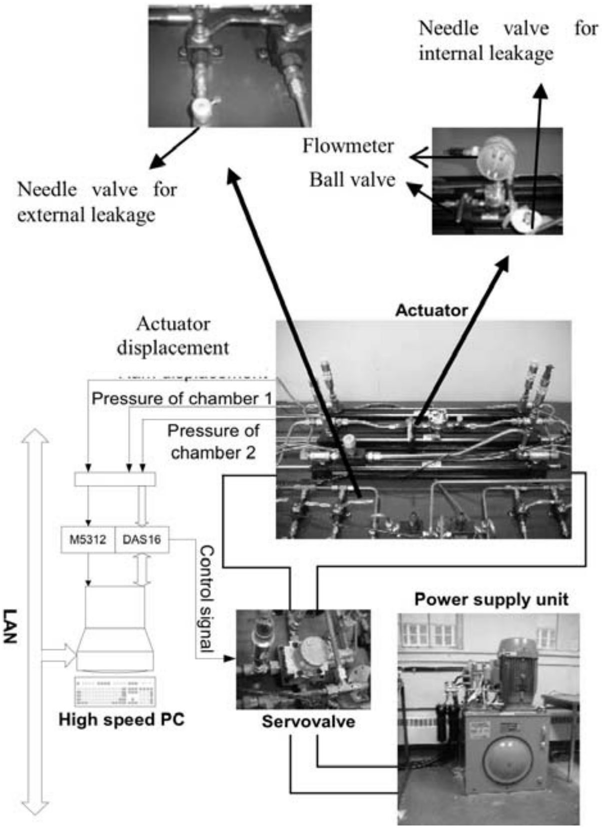

Fig. 1: *Test rig upon which all experiments are carried out*

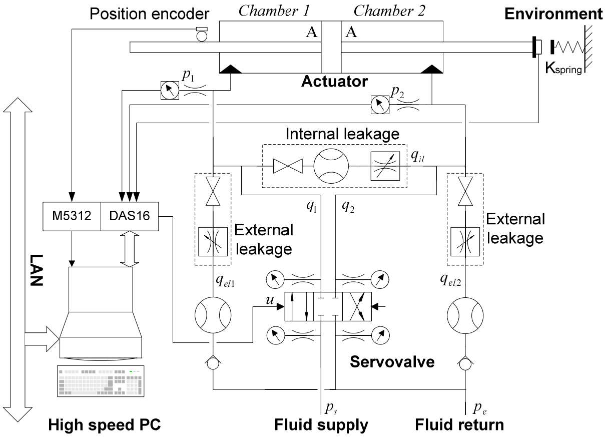

Fig. 2: *Internal and external leakage fault producing components*

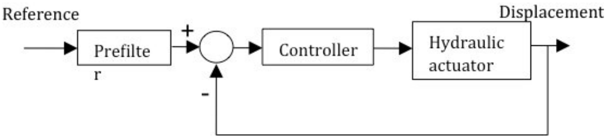

Fig. 3: *Two degree of freedom feedback system relating desired position to the actual position, in presence of stiffness dominant load*

3 Principle of Wavelet Analysis

The wavelet transform (WT) is a powerful signal processing tool that decomposes a nonstationary signal into scales (also known as levels) with different time and frequency resolution. As opposed to Fourier analysis that breaks up a signal into sine waves of different frequencies, wavelet analysis breaks up a signal into shifted and scaled versions of the original (mother) wavelet. The detailed mathematical descriptions of wavelet transform can be found in references (Daubechies, 1998) and (Vetterli and Herley, 1992). Here a brief description is provided.

Wavelet transform includes continuous wavelet transform (CWT) and discrete wavelet transform (DWT). The continuous wavelet transform is defined as the sum over all time of the signal multiplied by the scaled and shifted versions of the wavelet function ψ as:

$$\mathrm{CWT}(a,b)=\frac{1}{\sqrt{|a|}}\int_{-\infty}^{+\infty}x(t)\psi(\frac{t-b}{a})dt \tag{3}$$

where $\psi(t)$ is the mother wavelet and can be a complex conjugate. $a,b \in R$ (R is a real continuous number system) are the 'scaling' and 'shifting' parameters, respectively.

For most practical applications, the wavelet coefficients are discretized by a factor of $2^{m}n$ for shifting and by a factor of 2^{m} for scaling. The above equation then can be defined as:

$$\mathrm{DWT}(m,n)=2^{-m/2}\int_{-\infty}^{+\infty}x(t)\psi(2^{-m}t-n)dt \tag{4}$$

where m and n are integers. There exists the well-known 'multiresolution signal decomposition technique' (Mallat, 1989), for fast implementation of discrete wavelet transform. With reference to Fig. 4, the algorithm starts by applying low-pass filter (LPF) and high-pass filter (HPF) on the original discrete signal, $x[n]$, resulting in $a_1[n]$ and $d_1[n]$, where $a_1[n]$ is the approximation version of the original signal and $d_1[n]$ is the detailed version of the original signal.

Downsampling is done in the process of decomposition so that the resulting $a_1[n]$ and $d_1[n]$ each has $n/2$ points. Thus, the decomposition process can be continued, with successive approximations being decomposed in turn, so that the original signal is broken down into many lower resolution components.

4 External Leakage Detection via Wavelet Coefficients

4.1 Outline of the Approach

In the experiments, the more realistic case of the actuator following a pseudorandom reference positioning signal under a load emulated by a spring is considered. The pseudorandom signal is characterized with a series of desired step inputs having amplitudes between 0.025 m to 0.05 m and duration between 0.5 s to 4 s. This type of signal resembles activities of flaps for typical in-flight maneuvers (Nguyen et al., 1979), and thus allows us to investigate on-line fault detection ability of our method.

All experiments are conducted with QFT-based controller described by Eq. 1 and 2 and for small leakages, since they are most interesting for early detection of faults.

The first experiment relates to the case, where a healthy actuator undergoes a set of positioning tasks against a spring having stiffness of 80 kN/m. The resulting actuator displacements along with the desired one are shown in Fig. 5, with the existence of an external leakage, in chamber 2, after $t \approx 30$ s with the mean value of ≈ 0.3 L/min (see Fig. 6). As one can see the controller can still track the reference input without introducing any significant error even when there is an external leakage in the system after $t \approx 30$s.

The changes in the line pressures are plotted in Fig. 7. The external leakage causes pressure signals to drop, and can be considered as a bias fault (Goharrizi and Sepehri, 2011). When a bias or drift occurs in a signal, the event appears strongly in coarser scales represented by approximate coefficients of wavelet decomposition (Zhang and Yan, 2001). Thus, using the multiresolution signal decomposition technique, the pressure signal in one of the actuator's chambers can be decomposed into approximate wavelet coefficients, to detect this particular type of behavior in the original pressure signal. Note that processing the pressure signal, becomes important when a feature of interest is not strong in the original signal. However, even when a feature of interest is strong, it can be helpful to develop some types of automatic detection procedure (Anant, 1997).

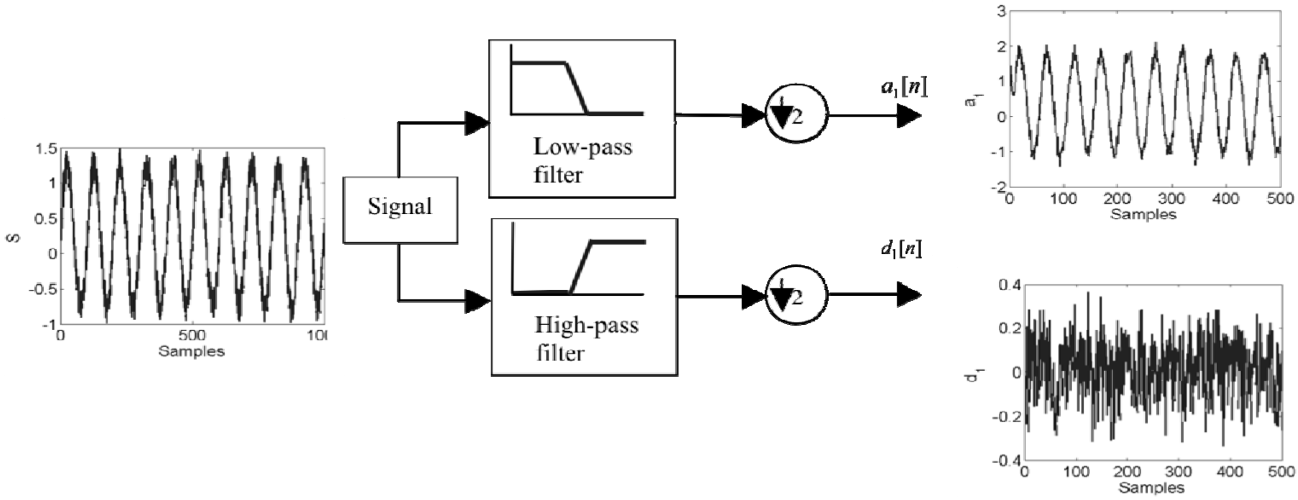

Fig.4: *Wavelet decomposition tree with one level of decomposition*

Given a sampling rate of 500 Hz, with a series of tests and comparison, level four approximate wavelet coefficient of system's pressure was found to be adequate to observe the effect of external leakage on the pressure signal (Goharrizi and Sepehri, 2011). Choosing scale four, a_4, for external leakage detection leads to have little computational burden as well as good sensitivity to this fault type. Daubechies 8 wavelet was found to be a good choice as the mother wavelet (Goharrizi and Sepehri, 2010a). The analysis was done on a program developed using MATLAB wavelet toolbox. Figure 8 shows level four approximate coefficient obtained from the pressure signal in chamber one, when a leakage (of average 0.3 L/min) is introduced in chamber 2 (see Fig. 6). Note that, one may choose the pressure signal in chamber two, P_2, for the analysis as shown in Fig. 9.

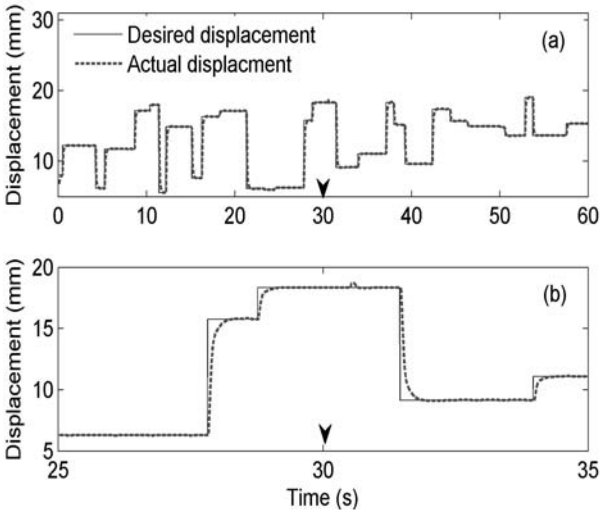

Fig. 5: *Desired and actual displacement of the hydraulic actuator with external leakage (chamber two) introduce at t ≈ 30 s: (a) whole operating time; (b) a close up between 25 - 35 s*

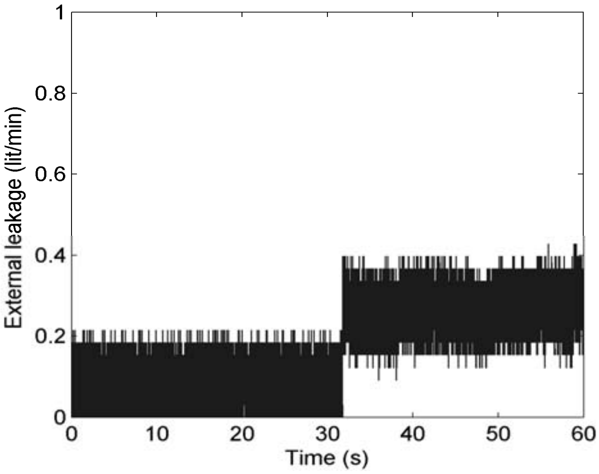

Fig. 6: *External leakage in chamber two of the hydraulic actuator (mean value: 0.3 L/min)*

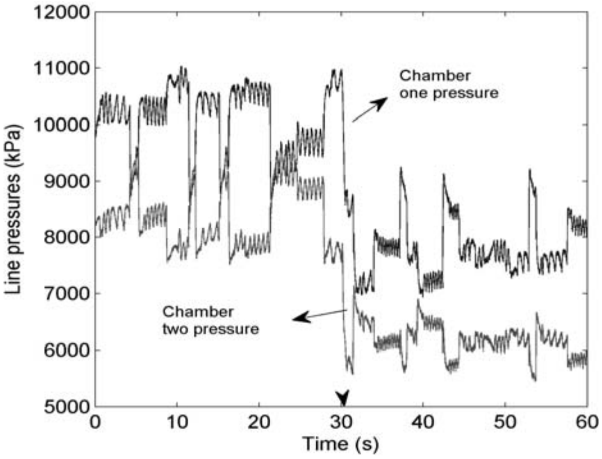

Fig. 7: *Line pressures with external leakage shown in Fig. 6*

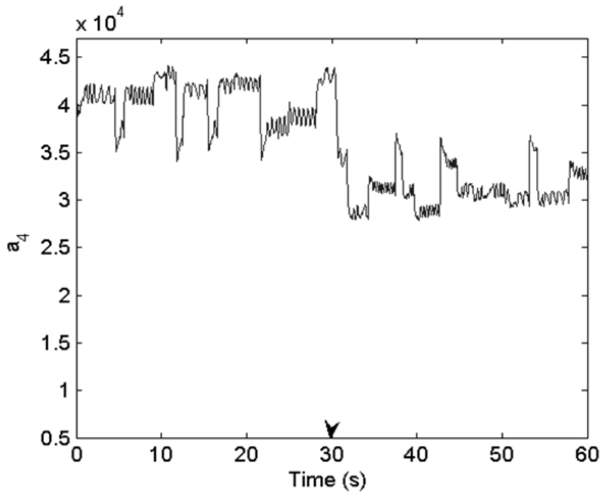

Fig. 8: *Level four approximate coefficient, a_4, obtained from the pressure signal at the chamber one with external leakage shown in Fig. 6*

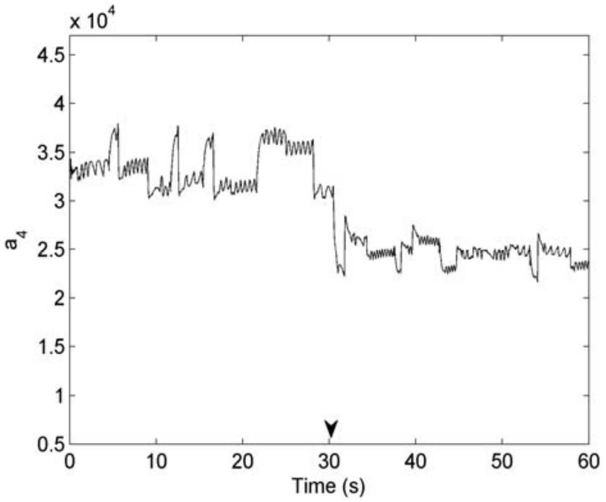

Fig. 9: *Level four approximate coefficient, a_4, obtained from the pressure signal at the chamber two with external leakage shown in Fig. 6*

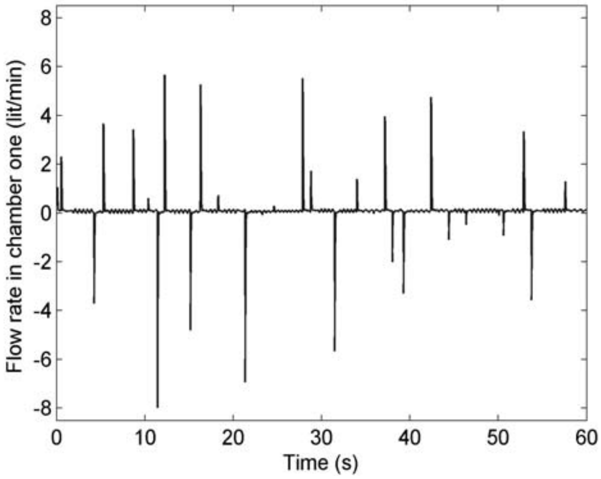

Fig. 10: *Flow rate in chamber one for healthy actuator given the desired input signal as in Fig. 5*

Note that the maximum flow rate for a healthy actuator in chambers one and two is about 6 L/min (see Fig. 10). Based on this value, the minimum leakage (0.3 L/min) represents approximately 5 % reduction of flow rate available to move the actuator.

4.2 Design for On-line Diagnosis

In an on-line equipment health monitoring, signals are monitored and gathered during the operation. Thus, the wavelet analysis should break each limited-duration data sequence into packets containing only the signal components within certain frequency bands. Here, the sliding window technique by Zhao and Xu (2004) is adopted to form data segments. With reference to Fig. 11, the data window has a length l_1. The past window contains data collected in the past and the current window which is the shift of the past window with a fixed step size l_2, contains data collected in recent time. Wavelet coefficients are repeatedly recalculated for intervals of l_2 samples, each based on the most recent l_1 samples of the signals. The root mean square (RMS) of the elements of vector of coefficients a_4 obtained from each window is then calculated as an index. Note that in order to extract reliable and complete information from the decomposed signals, each window should carry a sufficient length of data (Gao and Zhang, 2006). The length of the step size with respect to the window size should also be selected carefully. A small step size increases the computational cost and the nature of the windowed signal may not be sufficiently affected by the new data zone. A very large step size increases the detection delay as one needs to wait longer to update the relevant index. In this work, window size of l_1 = 400 samples and step size of l_2 = 20 samples were found to be appropriate.

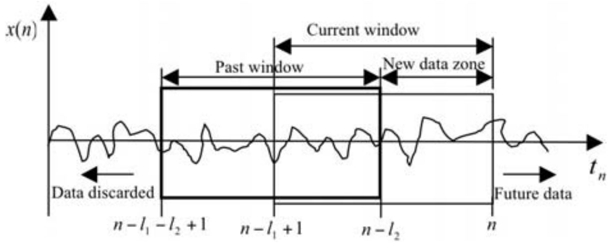

Fig. 11: *Presentation of sliding window technique*

The sliding window concept is now applied to the results of the case study reported in Section 4.1. The RMS values obtained from each updated window are plotted in Fig. 12. As is seen, the RMS values decrease once the external leakage is introduced to the system at t ≈ 30s. Whereas a_4 in Fig. 8 was obtained using the entire data (gathered over 60 seconds), the plot shown in Fig. 12, is the result of information being processed on-line.

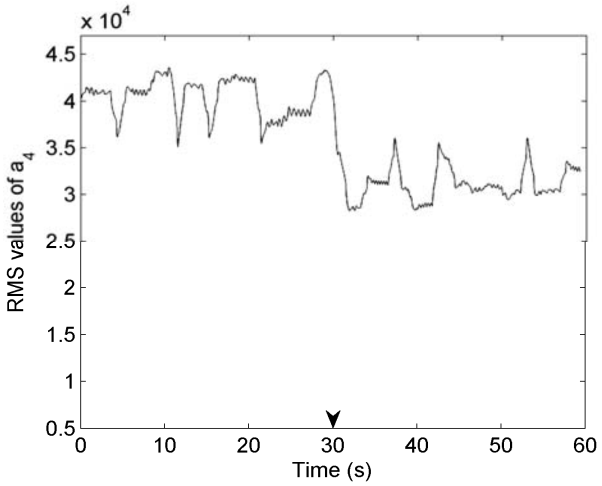

Fig. 12: *RMS values of level four approximate wavelet coefficient of chamber one pressure for actuator with external leakage shown in Fig. 6*

Another test was conducted with a more severe external leakage of value 0.94 L/min introduced at t ≈ 30 s (see Fig. 13) and given a reference input different from the one shown in Fig. 5 (see Fig. 14). The RMS values of a_4 using online measurements are depicted in Fig. 15. As compared to Fig. 12, the RMS values decreased more in this case. Therefore, given more severe external leakage, the RMS values of a_4 drop more, regardless the reference input. We repeated the above test given similar leakage level but with different reference position signals. Result of a typical test is shown in Fig.16. As one can see again, the RMS values show the same trend under existence of external leakage.

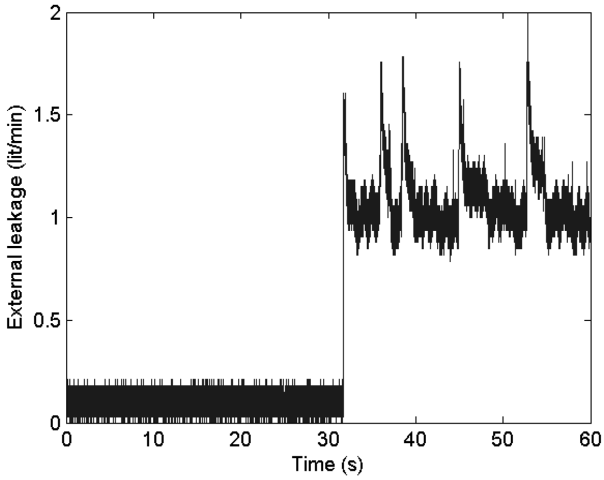

Fig. 13: *External leakage in chamber two of the hydraulic actuator with the mean value of 0.94 L/min*

The results have so far showed that pressure signal in either chamber one or chamber two can be analyzed for external leakage detection in any one of the two actuator's sides (chambers), which is consistent with the previous observations using the off-line approach (Goharrizi and Sepehri, 2011). However, using this technique, one cannot detect the leaky side of the actuator.

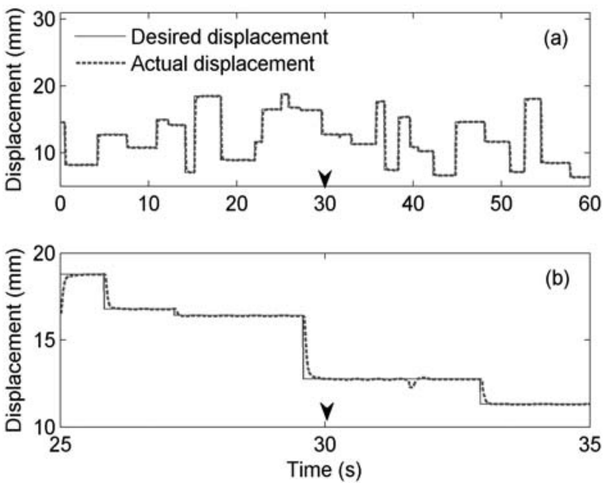

Fig. 14: *Desired and actual displacement of the hydraulic actuator with external leakage shown in Fig. 13: (a) entire operating time; (b) a close up between 25 - 35 s*

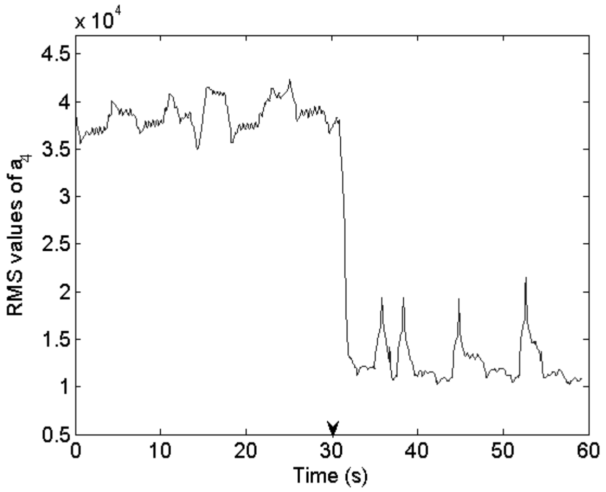

Fig. 15: *RMS values of level four approximate coefficients of chamber one pressure for actuator with the external leakage shown in Fig. 13*

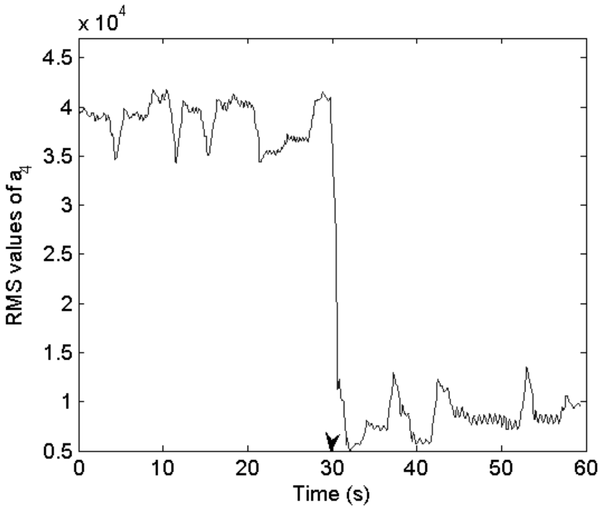

Fig. 16: *RMS values of level four approximate coefficients of chamber one pressure for actuator with an external leakage of approximately 0.94 L/min*

4.3. Isolation of External Leakage from Internal Leakage

In this section, the isolation of external leakage from internal leakage is investigated. These faults co-exist in an actuator, but are assumed to occur singly. Since this is an online application the likelihood of having both external and internal leakages at the same time is very small. For all results presented in this section, we use the pressure at chamber one, P_1 , for the analysis. We know from the previous work [16,17], that the internal leakage changes the transient behavior of the pressure signals, and subsequently decreases the amplitude and energy of level two detail coefficient, d_2 To further clarify this, we conducted another experiment in which the actuator experiences an internal leakage of the mean value of 0.48 L/min after t ≈ 30 s. The plots of leakage flow and actuator displacement are shown in Figs. 17 and 18, respectively. Again one can see the QFT position controller works well even in the presence of internal leakage. By applying the sliding window technique to the pressure data of chamber one, the RMS values of the wavelet coefficient, d_2, are calculated and plotted in Fig. 19. As one can see the peak values decreased as the result of internal leakage after t ≈ 30 s. To facilitate the comparison between healthy and faulty zones, a baseline value has been chosen for the RMS values.

Note that the frequency response of the system varies as a result of changes in the effective bulk modulus of the hydraulic functions caused by temperature changes or air content. However, by using wavelet transform the variation of frequency response is still within the range (62.5 - 125 Hz) and can be covered by d_2. This is indeed good and allows the wavelet transform based method to remain effective when the viscosity of hydraulic fluid changes. This observation was made by running the test rig for several times and is in line with findings previously reported (Goharrizi and Sepehri, 2010c).

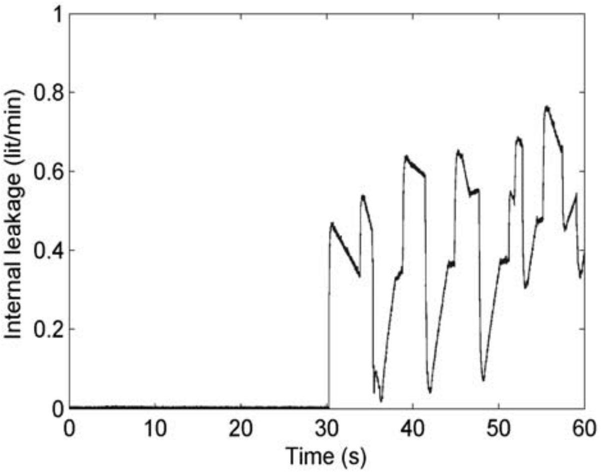

Fig. 17: *Internal leakage of 0.48 L/min in average at t ≈ 30 s*

Next, we show that the coefficient, a_4, is not sensitive to the internal leakage, which was shown to be sensitive to the external leakage. As compared to Fig. 12 and 15, one can see from Fig. 20 that the trend of, a_4, is not changed by the internal leakage after t ≈ 30 s. Therefore, the wavelet coefficient, a_4, is not sensitive to the internal leakage fault.

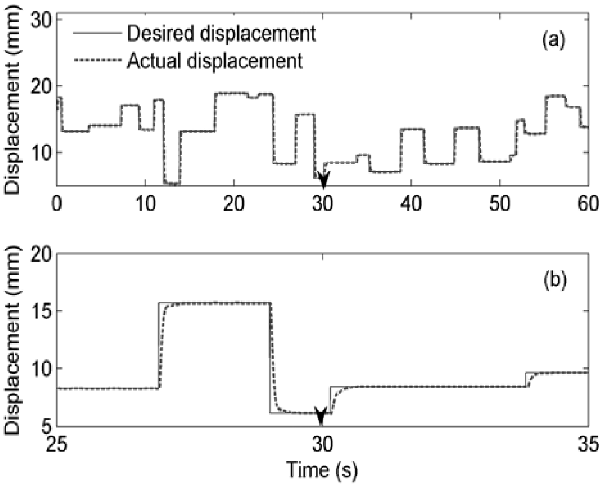

Fig. 18: *Desired and actual displacement of the hydraulic actuator with internal leakage shown in Fig. 17: (a) whole operating time; (b) a close up between 25 - 35 s*

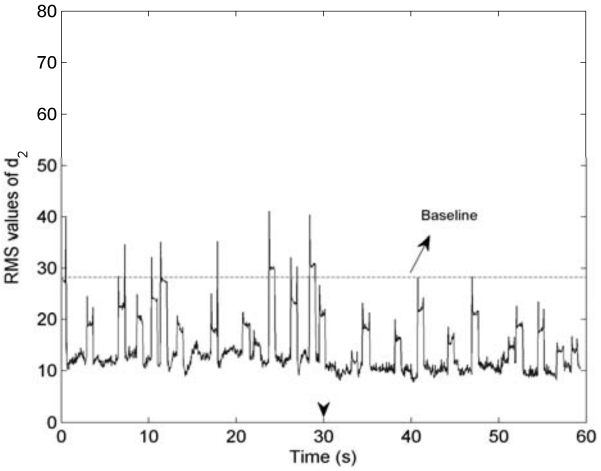

Fig. 19: *RMS values of level two detail coefficients of chamber one pressure for actuator with internal leakage shown in Fig. 17*

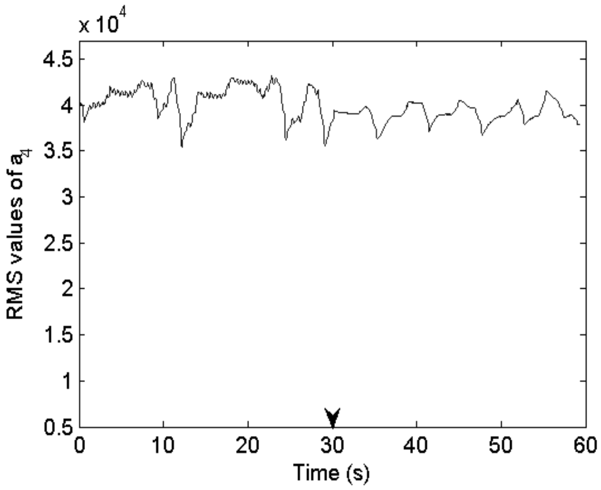

Fig. 20: *RMS values of level four approximate coefficients of chamber one pressure for actuator with internal leakage shown in Fig. 17*

We now investigate if the wavelet coefficient d_2 is sensitive to external leakage or not. The RMS values of d_2 associated with the external leakage in Fig. 13 are depicted in Fig. 21. Given the same baseline as in Fig. 19, one can see, these values are still above the baseline value after the occurrence of external leakage after $t \approx 30$ s. However, the RMS values of the low frequency wavelet coefficient a_4 decrease as a result of external leakage (see Fig 15).

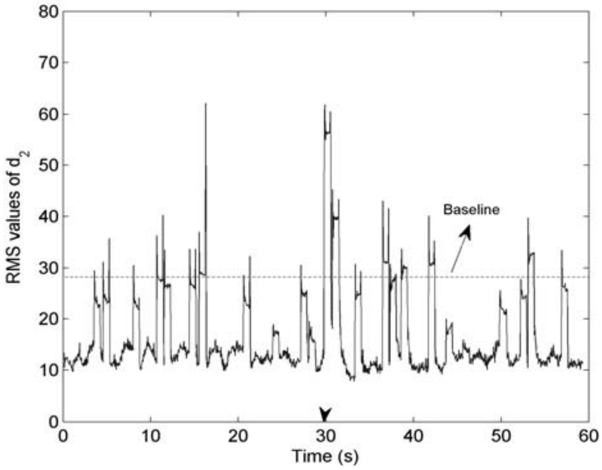

Fig. 21: *RMS values of level two detail coefficients of chamber one pressure for actuator with external leakage shown in Fig. 13*

It is therefore, concluded that coefficients a_4 and d_2 are independently sensitive to the effect of external and internal leakages, respectively. Thus, by inspecting them, one can not only detect external and internal leakages but also isolate them when they happen singly in a multiple-fault environment.

5 Conclusion

A wavelet-based approach was employed for external leakage fault detection and its isolation from internal leakage in hydraulic actuators. A realistic situation in which the actuator tracks a pseudorandom reference input in a closed loop scheme under loading condition was considered. The use of easily measurable pressure at any one of the actuator chambers was found to be a valuable source of signal that carries sufficient information to support reliable diagnosis. Multiresolution technique was used to break a finite-length pressure signal (obtained on-line) into smoothed and detailed versions in the terms of discrete approximate and detail wavelet coefficients. The finite-length pressure signal due to a pseudorandom reference input was collected using a sliding window technique. It was then demonstrated that the RMS values of level four approximate coefficient is sensitive to external leakage and can be considered as an index to distinguish between healthy and faulty operating conditions. Additionally, this index was shown to be sensitive to the amount of external leakage flow. The more severe the external leakage is, the smaller the value of this index. By monitoring this index, one can detect external leakage as low as 0.3 L/min. We further showed that, isolation of external leakage from internal leakage, when they happen singly in a multiple-fault environment is possible with only one measurement and without a need to include the model of actuator and/or leakage. All the above results could be achieved regardless of the type of feedback controller used, reference input and loading condition. However, this method cannot distinguish between the external leakages on either side of the actuator.

Nomenclature

$x(t)$	Signal at time t	
$\psi(t)$	Mother wavelet	
$h[..]$	Impulse response of low-pass filter	
$g[..]$	Impulse response of high-pass filter	
a_i	Approximate wavelet coefficient at level i	
d_i	Detail wavelet coefficient at level i	
l_1	Window size	
l_2	Step size	
P_1,P_2	Pressures in chamber one and two	[kPa]

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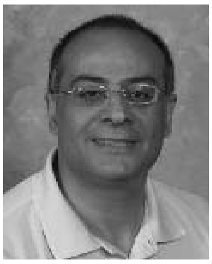

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